Welding Design and Construction

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(This paper describing work on an all welded radio tower was awarded the 1943 Lincoln Arc Welding Foundation prize of $250 for the best paper describing arc welding construction.)

WELDING has come into prominent use in the radio tower industry during the past decade. A common type of radio tower is the shop-welded triangular steel radio tower which is fabricated in sections approximately 20 feet in length. This type of tower is an equilateral triangle in cross section with the same length sides throughout its entire height. Guys, spaced 120° apart, are usually attached at one or more levels of the tower. This type of tower is most economical when compared with other types of towers if the total height is greater than approximately 250 feet.

The purpose of this paper is to present the design of a tower of this type. One of the problems met in this design is the value of L to use in the $\frac{L}{R}$ ratio for the design of the web and column members in compression. Specifications usually give a maximum value of 120 for the $\frac{L}{R}$ ratio of the tower as a whole and for the column members, and 180 for the web members.

An experimental investigation of a section of a tower of this type was presented in 1943 by the authors as a thesis for their degrees in engineering. The section tested in this thesis was fabricated with a modified Warren web system called the "Shelton" web system. A developed view of the test section is shown in figure 1.

Combined stress, bending plus direct stress, was obtained at various locations on the members of the tower with Huggenberger tensometers. The gauges are shown in position in figure 2. The various gauge locations on a column member are shown in figure 1. Three gauge readings, spaced 120° radially, were taken at each location. By averaging the three combined stresses found at each location the average direct stress, $\frac{P}{A}$, was found. This average direct stress was subtracted from each combined stress to get the bending stress at each gauge location. The direction of the neutral axis and the value of the maximum bending stress was found for each location by a graphical method. The maximum bending stress at each successive point on a member was plotted. The direction of the neutral axis was carefully observed so that points of contraflexure could be spotted. L, the distance between points of contraflexure, was scaled from the graphs. The average L for a typical column member is 28.1 inches or 0.84 of the distance between joints on a column member (a panel length). Values of L were obtained for each of the three column members when the section was tested as a column and for one column member when the section was loaded as a beam. From the results of these tests a full panel length was recommended as a safe and conservative L for the design of the column members.

The gauges were used and the data reduced in the same manner for the web members as for the column member. However, the web members were tested only under the beam loading. From these tests an L of 0.7 of its length was recommended for the short web members and an L of 0.6 of its length for the long web members. These tests also indicated that considerable fixity of the web members was produced by the welds. The long web members showed a greater degree of fixity than the short web members because of the greater perimeter of weld material on the longer web members.

Two similar sections, one with the Shelton web system and the other with the true Warren web system, were tested to failure. These sections were loaded as beams when they were failed. Both sections failed by the buckling of compression web members of the section. The failure load of the section with the Shelton web system was higher than the failure load for the section with the Warren web system. Because of its apparently greater strength the Shelton web system will be used in this design problem. The buckling of the web members showed pictorially that partial fixity of the web members was produced by the welds. Very little bending occurred at the welds. A picture of the failure of the section with the Shelton web system is shown in figure 3.

DESIGN OF THE TOWER

For the purpose of this problem a tower is designed having the dimensions shown in figure 4.

The total height of the tower is 290 feet. The tower is braced by three guys, radially spaced 120° apart, fastened to the tower 190 feet above the base of the tower. The ground connections of the guys are 270 feet from the base of the tower. The letters and symbols used for the various distances and angles are shown in figure 5.

Specifications

The allowable $\frac{L}{R}$ for the tower legs is equal to or less than 120.

The allowable $\frac{L}{R}$ for the webs members is equal to or less than 180.

The allowable $\frac{L}{R}$ for tower as a whole is equal to or less than 120.

For an $\frac{L}{R}$ up to 120, $f = 17{,}000 - 0.485 \left(\frac{L}{R}\right)^2$ lb/sq. in.

For an $\frac{L}{R}$ from 120 to 200, $f = \dfrac{18{,}00}{1 + (1/18{,}000)\left(\frac{L}{R}\right)^2}$ sq. in.

Members that are subjected to both axial and bending stresses shall be so proportioned that

$\frac{f_a}{F_a} + \frac{f_b}{F_b}$ shall not exceed unity

F_a=axial unit stress that would be permitted by this specification if axial stress only existed.

F_b=bending unit stress that would be permitted by this specification if bending stress only existed.

f_a=axial unit stress (actual)=axial stress divided by the area of the member.

f_b=bending unit stress (actual)=bending moment divided by the section modulus of the member.

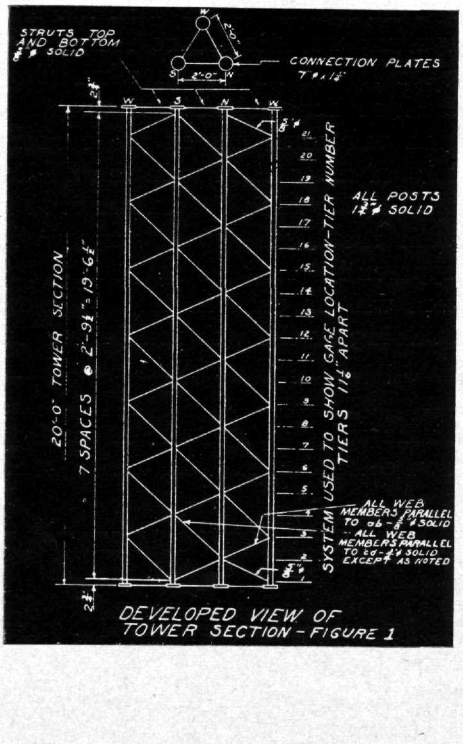

Figure 1

The allowable tension in structural steel is 20,000 lbs./sq. in.

Members subject to stresses produced by a combination of wind and other loads are proportioned for unit stresses 1⅓ greater than the allowable stresses previously mentioned.

Assumptions

The wind force is assumed to be 25 lbs/sq. ft. of exposed surface area. The effective surface area of the mast is taken as the cross section of the members of the tower. The minimum size members allowed by the $\frac{L}{R}$ ratio are used in figuring the exposed surface area.

The general dimensions of the tower are arrived at as follows. The $\frac{L}{R}$ of the tower as a whole is equal to or less than 120. The maximum unsupported length of the tower is 190 feet, the distance below the guy connection.

$$R = \frac{L}{120} = \frac{190}{120} = 1.583 \text{ feet.}$$

The radius of gyration (R) of the tower as a whole is equal to (.408) (length of the side of the tower).

The length of the side $= \frac{1.583}{.408} = 3.88$ feet minimum.

A distance of 4 feet from center to center of columns is used in the design of the tower.

The $\frac{L}{R}$ ratio of the column members shall not exceed 120.

$$R = \frac{L}{120} = \frac{54}{120} = .45 \text{ inches}$$

The radius of gyration (R) of a circle $= \frac{\text{Diameter}}{4}$

The minimum allowable diameter=4xR=4x.45 =1.80 inches.

A 1⅞ inch diameter or larger round bar must be used for the column members.

The $\frac{L}{R}$ ratio of the web members shall not exceed 180. The safe free length L for the web members, as found by experimentation, is 0.7 of the total length (l) of the web.

For the longer web (60 in.), $R = \frac{L}{180} = \frac{(.7)(l)}{180} =$ .233 inches.

D=4xR=4x.233=.934 inches minimum diam.

Therefore a 1 inch diameter or larger round bar must be used for the longer web members.

For the shorter web (51.25 in.),

$$R = \frac{L}{180} = \frac{(.7)(51\frac{1}{4})}{180} = .199 \text{ in.}$$

D=4xR=4x.199=.796 inches minimum diam.

Therefore a 7/8 inch diameter or larger round bar must be used for the shorter web members.

Therefore, with the wind blowing perpendicular to one face of the tower, the minimum area presented to the wind per panel of tower (54 inches) is as follows:

$$\begin{aligned} 51.25\text{x } 7/8 &= 44.9 \text{ sq. in.} \\ 60.00\text{x } 1 &= 60.0 \text{ sq. in.} \\ 3\text{x}54.00\text{x}1\,7/8 &= 303.5 \text{ sq. in.} \\ \cos 30\text{x}2\text{x}60.00\text{x}1 &= 60.0 \text{ sq. in.} \\ \cos 30\text{x}2\text{x}51.25\text{x } 7/8 &= \underline{44.9} \text{ sq. in.} \end{aligned}$$

Area obstructing the wind=513.3 sq. in. per panel

$\frac{513.3}{144} \text{ x } \frac{12}{54} = .79$ sq. ft. (minimum)/vertical foot of tower.

A conservative area of 1 sq. ft. per vertical foot of tower is used in the design.

Therefore the wind per vertical foot of tower equals 1x25=25 lb./foot of tower.

The critical wind condition exists when the wind is acting over the whole tower simultaneously. The shear and moment diagrams for the tower when the critical condition exists are shown in figure 5.

Moments are taken about point C, the base of the tower.

$$R_A = \frac{(w)\ (L)^2}{2\text{x}190} = \frac{(25)\ (290)^2}{2\text{x}190} = 5530 \text{ pounds.}$$

Moments are taken about point A, the point of guy attachment.

$$R_C = \frac{\frac{190)^2(25)}{2} - \frac{(100)^2(25)}{2}}{190} = 1720 \text{ pounds.}$$

Design of the Guy Cables

For the first trial a 7/8 inch high strength cable is assumed.

The Modulus of Elasticity=20,000,000 lb/sq. in.

The breaking load=66,000 pounds.

The safe working load=13,200 pounds.

The weight of the cable=1.20 lbs./foot of cable.

The total weight of the cable=1.20x330=396 lbs.

The weight of 4 insulators at 57½ lbs. each=230 lbs.

Total=626 lbs.

$$w = \text{the load per horizontal foot} = \frac{626}{270} = 2.32 \text{ lbs.}$$

The net area of the cable cross section is equal to

$$\frac{\text{Weight per foot of cable}}{\text{Weight of 1 foot of solid steel, 1 inch in cross sec.}}$$

$$= \frac{1.20}{490/144} = .353 \text{ sq. in. net area.}$$

The length of the cable due to dead weight only is solved as follows:

$$(1) \quad \text{Length} = L = a \left(\sec\theta + \frac{8\Delta^2}{(3)\ (a)^2\ (\sec^3\theta)} \right)$$

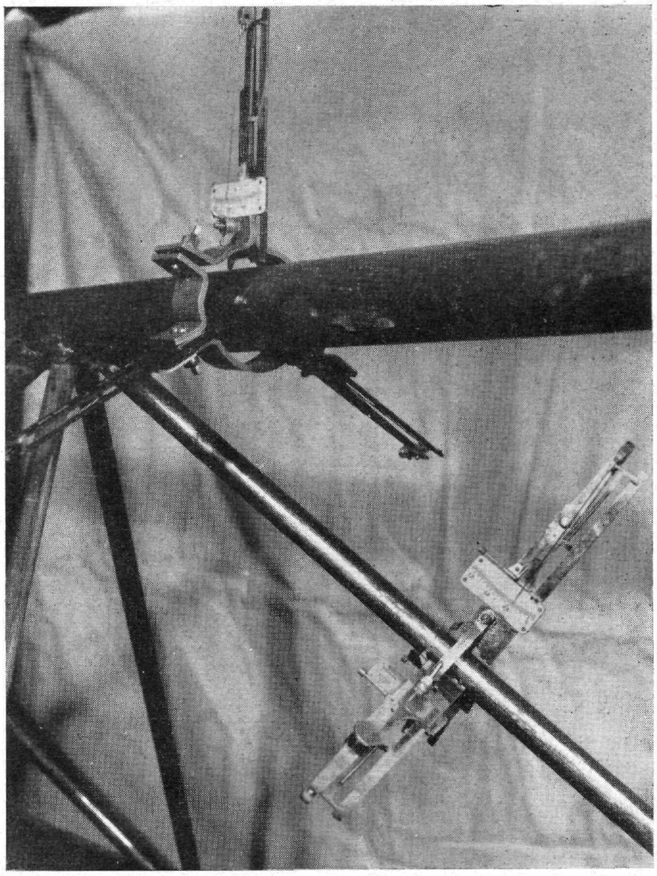

Figure 2

$$(2) \quad \Delta = \frac{(w)\ (a)^2}{(8)\ (H)} = \text{the deflection at}$$

the mid-point of the cable as shown in figure 5.

$$(2) \quad \Delta = \frac{(2.32)\ (270)^2}{(8)\ (6870)} = 3.08 \text{ ft. deflection}$$

from the dead load alone.

$$(1) \quad \text{length} = 270 \left(\frac{330.151}{270} + \frac{(8)\ (3.08)^2}{(3)\ (270)^2\ (1.2228)^3} \right) = 330.202 \text{ ft.}$$

The maximum stress in guy X occurs when the wind is blowing perpendicular to guy Y.

The horizontal component of X (max)=1.155xP

The horizontal component of Y (concurrent)=0.577xP

The wind force is assumed to be effective over ⅔ of the total area of the guys. The reaction from the wind on the guys=(7/8) (1/12) (⅔) (330x3x25)=1200 lbs. total.

One-half of this total reaction (1200 lbs.) goes to the mast and one-half to the ground attachment.

$$P = R_A + \frac{1200}{2} = 5530 + 600 = 6130 \text{ lbs.}$$

The horizontal component of X (max)=1.155x6130=7080 lbs.

The horizontal component of Y (concur.)=.577x6130=3540 lbs.

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WELDING DESIGN

(Continued from page 9)

These horizontal components of the wind stresses in the guys are true only if there is no horizontal movement of the tower at point A and, consequently, no change in the initial stress in the guys. Actually point A will deflect, relieving part of the initial stress in cable Z, when the tower is loaded. The release of part of the initial tension in Z relieves an equal amount of the initial tension in the other guys. (This principle is the same as the one involved in bridges with counters.) The amount of this relief must be determined by trial. The relief of the initial tension in Z is assumed to be 5470 lbs.

The horizontal component of the relief of the initial tension$=5470\text{x } \cos\theta=5470\text{x } \cos 35^\circ\ 08'=$ 4470 lbs.

It is customary to erect the tower with an initial stress in the guys of approximately one-eighth of the breaking load; in this case 8400 lbs.

The horizontal component of the initial stress (tension) in the guys$=8400 \cos\theta=6870$ lbs.

Total concurrent Horizontal Reactions (Initial plus wind)

H=Initial Stress—Release+Wind Stress.

$H_x=6870-4470+7080=9480$ lbs.

$H_y=6870-4470+3540=5940$ lbs.

$H_z=6870-4470+\quad 0=2400$ lbs.

Total Stress in the Guys$=$H x sec θ

$X=9480 \text{ x } \sec\theta=11{,}620$ lbs.

$Y=5940 \text{ x } \sec\theta=\ 7{,}260$ lbs.

$Z=2400 \text{ x } \sec\theta=\ 2{,}930$ lbs.

Stress in the Guys Caused by the Wind Only

Stress=horizontal component of wind stress times sec θ.

$X=7080 \text{ x } \sec\theta=8660$ lbs.

$Y=3540 \text{ x } \sec\theta=4330$ lbs.

$Z=-5470 \qquad =-5470$ lbs. (relief is negative tension).

Unit Stress in the Guys Caused by Wind Only

Unit Stress=Wind stress in guy/cross section area.

$X=\dfrac{8660}{.353}=24{,}540$ lbs./sq. in.

$Y=\dfrac{4330}{.353}=12{,}260$ lbs./sq. in.

$Z=\dfrac{-5470}{.353}=-15{,}500$ lbs./sq. in.

Stretch of the Guys Caused by Wind Stress Only

$$\text{Stretch}=\frac{(\text{Stress})\ (\text{Length})}{\text{Modulus of Elasticity}}$$

$$\text{Stretch of } X=\frac{24{,}550\text{x}330.202}{20{,}000{,}000}=.405 \text{ feet}$$

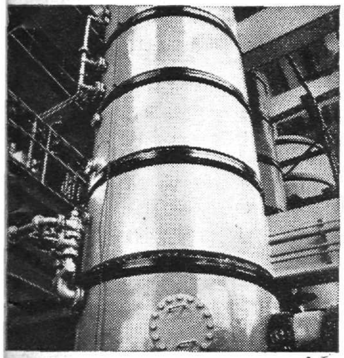
$$\text{Stretch of } Y=\frac{12{,}260\text{x}330.202}{20{,}000{,}000}=.202 \text{ feet}$$

$$\text{Stretch of } Z=\frac{-15{,}500\text{x}330.202}{20{,}000{,}000}=-256 \text{ feet}$$

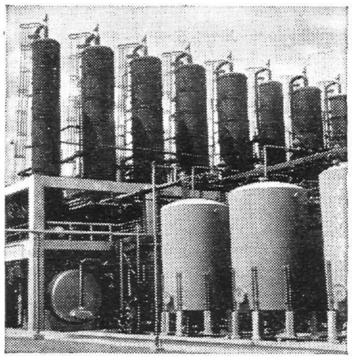
(Due to the extreme length of this article it will be concluded in the December issue.)

TEN YEARS' WORK IN TWO

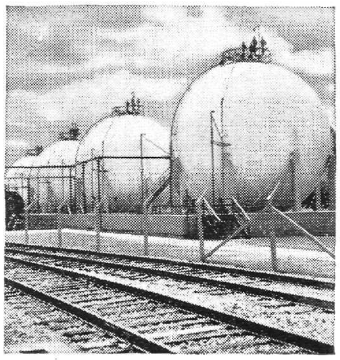
is the story behind Butadiene and Styrene for Synthetic Rubber



Distillation Column for Styrene



Where Distillation Columns separate and purify the Butadiene



Butadiene Storage Spheres

WE WISH YOU could see the first of the Government's large integrated synthetic rubber projects, complete at one location. What you see here is a night scene and some daytime views of the immense butadiene and styrene plants that CARBIDE AND CARBON CHEMICALS CORPORATION, a Unit of UCC, has designed and built at Institute, West Virginia, for the Government's Defense Plant Corporation and is operating for the Rubber Reserve Company.

Carbide and Carbon also has completed another butadiene plant at Louisville, Kentucky —and has released plans to Koppers United Company for a third butadiene plant near Pittsburgh, Pennsylvania.

Butadiene had never been manufactured in the United States in large quantities before the plants at Institute went into production. The task involved in providing the mass production facilities the Government asked for was an unusual one...but one that took full advantage of the experience and processes developed by Carbide and Carbon.

Generally, it requires seven to ten years for a company to take a process developed in the laboratory, put that process to test in a pilot plant, iron out production problems, design a full-size plant, and then actually build the plant and go into mass production.

By working at top speed for twenty months —Carbide and Carbon telescoped research, development, engineering, and construction work that would have taken 10 years in normal times. In this short time laboratory research was translated through chemical engineering into larger and more modern facilities for producing the chemicals for synthetic rubber than existed anywhere else in the world.

This achievement could never have been possible had it not been for the years of research and experimentation which, prior to the emergency, Carbide and Carbon had devoted to the production of synthetic—or man-made—chemicals of the organic series.

Business men, technicians, teachers, and others are invited to send for the book "Butadiene and Styrene for Buna S Synthetic Rubber from Grain Alcohol" which explains what these plants do, and what their place is in the Government's rubber program.

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BUTADIENE, (bew-ta-dý-een). A highly volatile liquid which is the principal chemical in the manufacture of Buna synthetic rubbers.

STYRENE, (stý-reen). A liquid, like benzene, but having the property of reacting within itself to form a solid, clear, plastic mass. It is used as one of the principal ingredients of Buna S synthetic rubber.

BUY UNITED STATES WAR BONDS AND STAMPS

CONSTRUCTION RECORD AT INSTITUTE

June 25, 1941 — Carbide and Carbon submits definite production estimates.

July 31, 1941 — Design work starts on 10,000-ton-a-year butadiene unit.

Aug. 22, 1941 — Government authorizes construction.

Dec. 7, 1941 — Pearl Harbor

Dec. 15, 1941 — Design "frozen" for 20,000-ton-a-year alcohol-to-butadiene plant.

March, 1942 — Japanese occupy Malay Peninsula and Dutch East Indies; cut off about 90 per cent of U. S. natural rubber supply.

April, 1942 — Construction on the first of four 20,000-ton-a-year butadiene units starts at Institute, W. Va.

July, 1942 — Construction of 25,000-ton-a-year styrene plant starts.

Sept. 10, 1942 — Rubber Survey (Baruch) Committee report accepted.

Jan. 29, 1943 — First large-scale, alcohol-to-butadiene unit goes into operation two months ahead of schedule.

April 7, 1943 — First styrene unit begins operation.

May 25, 1943 — Fourth 20,000-ton-a-year butadiene unit begins operation at Institute plant.

August, 1943 — Four 20,000-ton-a-year butadiene units producing at rate of 120,000 tons a year—50% over rated capacity.

UNION CARBIDE AND CARBON CORPORATION

30 East 42nd Street UCC New York 17, N. Y.

Principal Products and Units in the United States

ALLOYS AND METALS
Electro Metallurgical Company
Haynes Stellite Company
United States Vanadium Corporation

CHEMICALS
Carbide and Carbon Chemicals Corporation

ELECTRODES, CARBONS & BATTERIES
National Carbon Company, Inc.

INDUSTRIAL GASES AND CARBIDE
The Linde Air Products Company
The Oxweld Railroad Service Company
The Prest-O-Lite Company, Inc.

PLASTICS: Bakelite Corporation • Plastics Division of Carbide and Carbon Chemicals Corporation